PROGRESS IN MODELING DEFORMATION AND DAMAGE

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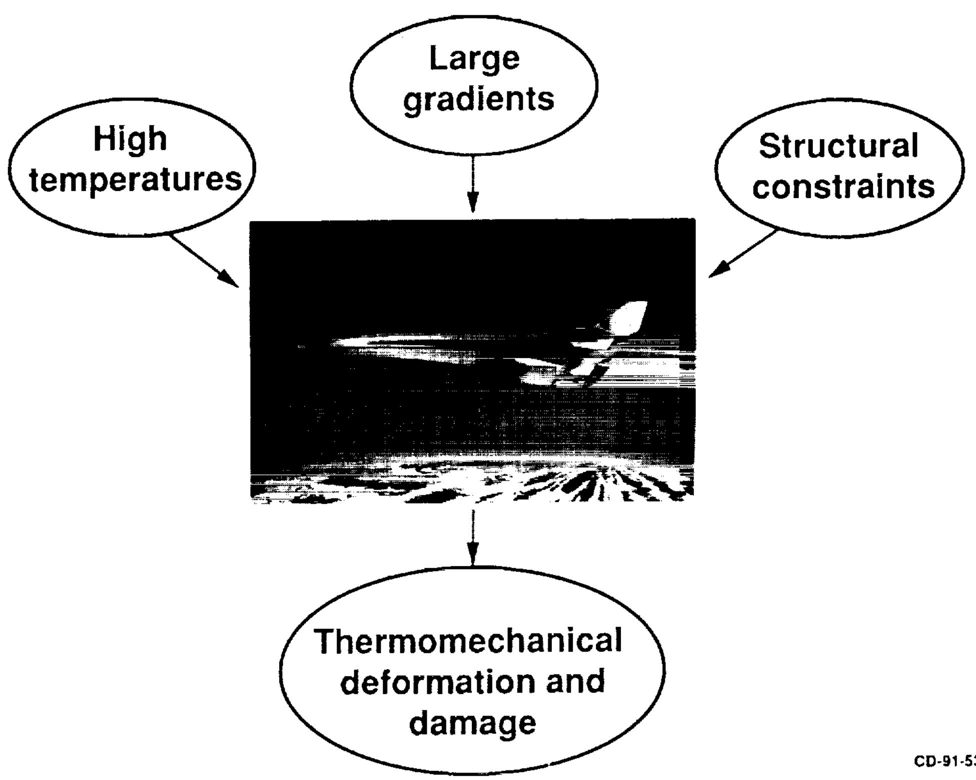
In hypersonic aircraft, for example, high-temperature structures (such as leading edges, inlet cowls, combustor liners, and nozzles) are subjected to thermomechanical deformations. It is believed that such deformations will be a primary cause of structural failure in these components. They arise from large thermal gradients across structural skins that are constrained from free thermal expansion. In order to assess structural life and performance, the material's thermomechanical behavior must be incorporated into the structural design. The laboratories of the Fatigue and Fracture Branch are dedicated to observing the evolution of deformation and damage in laboratory specimens under thermomechanical loading conditions. These observations are used within the Branch to guide the development of deformation and life-assessing models.

Problem Statement



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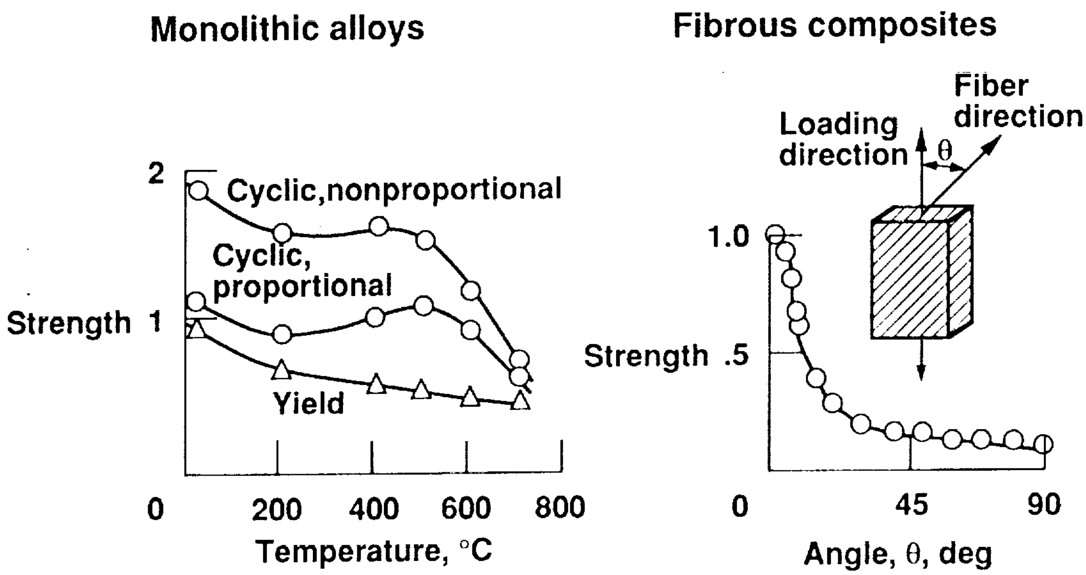
Material Characterization



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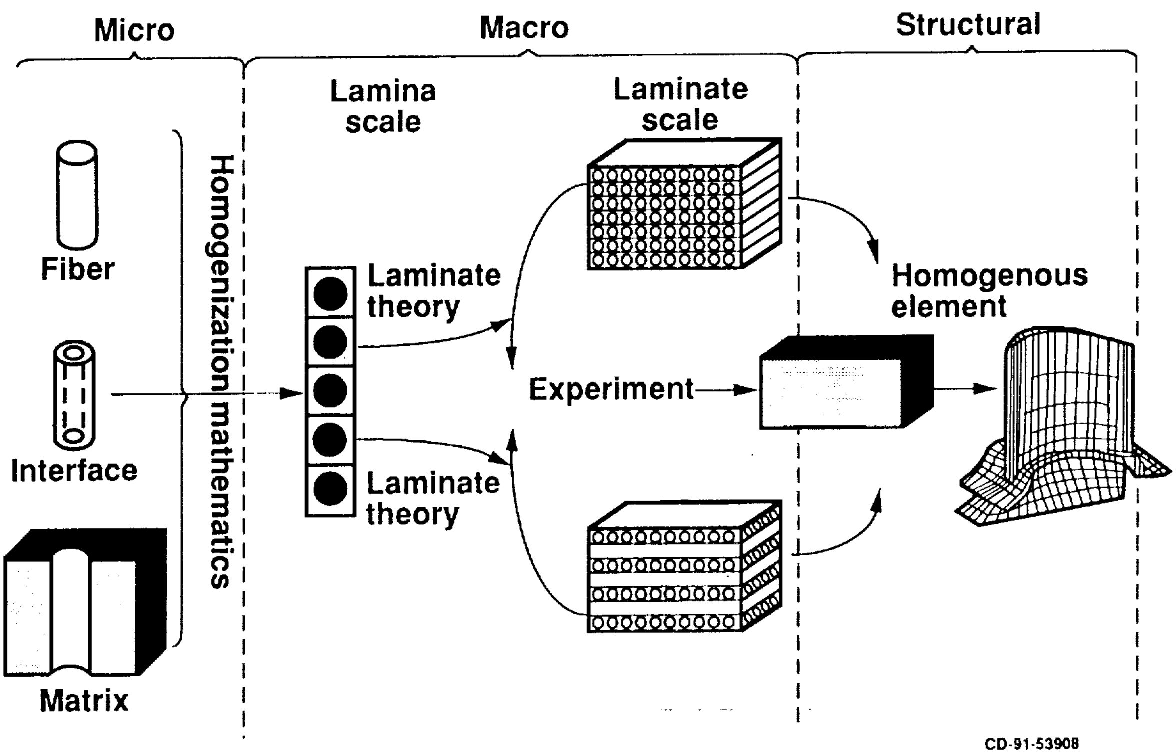
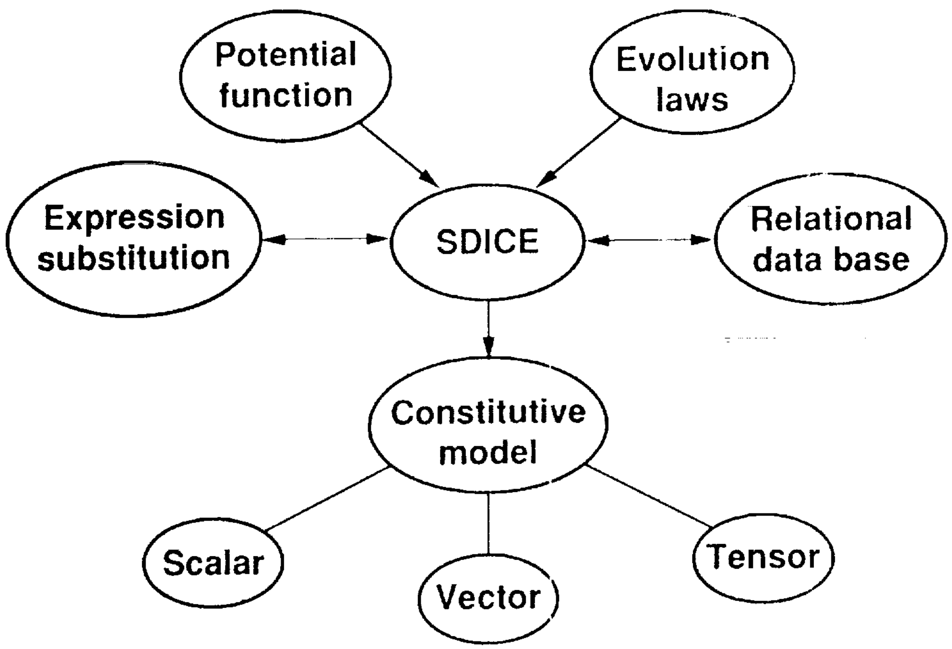
Viscoplastic monolithics and composites both offer many challenges to the viscoplastic model developer. The development of realistic models requires experiments that probe a material's response for a wide variety of inputs. One facet of monolithic material behavior is how temperature and loading history interact to affect material strength. Many alloys gain strength over their original yield strength when they are cyclically loaded. Furthermore, strengthening is often greater in nonproportional cyclic histories than in proportional ones. Also strength does not decay monotonically with increasing temperature. An important feature of composite material behavior is the anisotropy in the structure's strength. For a unidirectional fibrous composite the yield strength falls off rapidly as the axis of loading deviates from that of the fibers in the composite. The loading cone must have a small angle for this type of composite if the designer is to make maximum use of the composite's strength.

Scales in Composite Analyses



NASA Lewis is investigating two approaches for developing a constitutive model of a fibrous composite whose matrix is viscoplastic and whose fiber is elastic. The first is a micromechanics approach, where the constitutive models for each phase of the composite (i.e., fiber, interface, and matrix) are combined by using homogenization techniques. The result is a constitutive model for the composite. In this approach the geometry of the composite is handled through the mathematics of homogenization. The second approach is a macromechanics one, where the composite is treated as an anisotropic continuum. In this approach the geometry of the composite is handled through the choice of invariants used to describe the anisotropy. Here the constitutive model is defined at a larger scale than is the micromechanics model, and consequently it cannot provide stress and strain information at the constituent (phase) level.

Symbolic Computations



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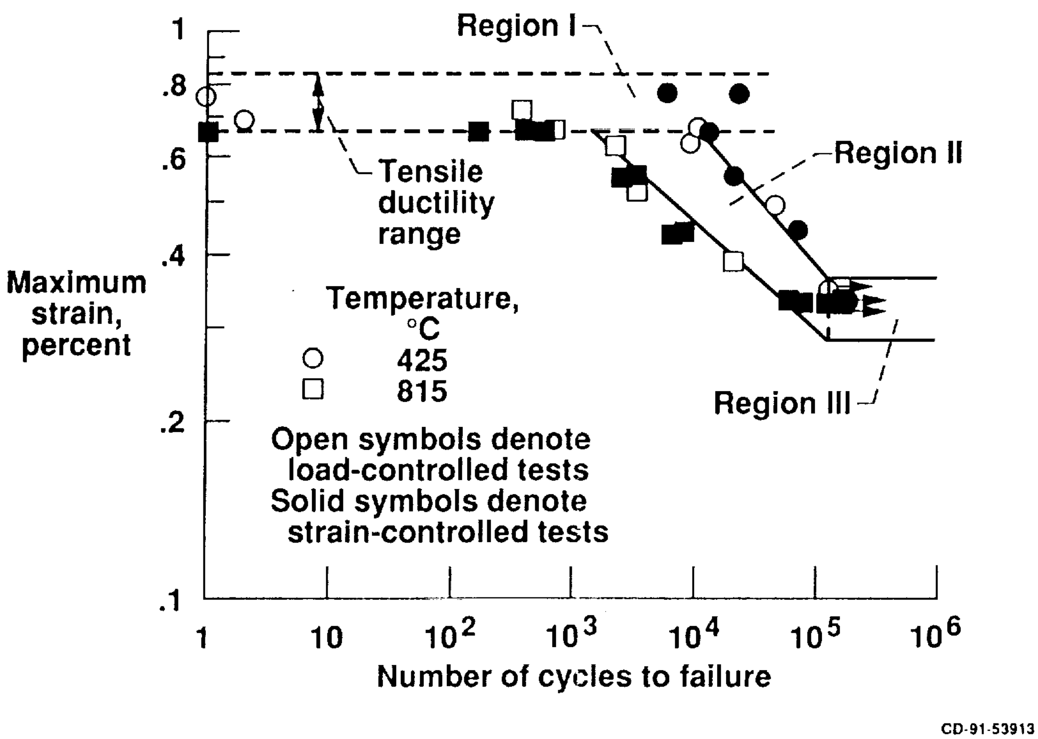
The development of new constitutive equations (e.g., viscoplastic models) can be time consuming, involved, and error prone; therefore, an intelligent application of symbolic systems to facilitate this tedious process can be of significant benefit. A self-contained symbolic expert system, named SDICE, is being developed under NASA Lewis support. This package is capable of efficiently deriving potential-based constitutive models in analytical form. These potential equations can be scalar, vector, or tensor valued. A unique feature of SDICE is its ability to identify common terms found in two or more locations, to assign variables to those terms, and to substitute these variables back into the equations. This important feature minimizes expression growth, which is probably one of the most plaguing problems confronting existing symbolic codes.

Fatigue Life Diagram of MMC's and IMC's



Viscoplastic models are defined by a system of mathematically stiff, coupled, nonlinear, first-order, ordinary differential equations. In other words, their numerical integration is "expensive." As a consequence, much research has been expended in the development of efficient and accurate numerical integration methods for solving viscoplastic problems. Probably the most exciting developments in numerical integration theory to come along in many decades are the Walker-Freed asymptotic integration algorithms recently developed at NASA Lewis. For the differential equation

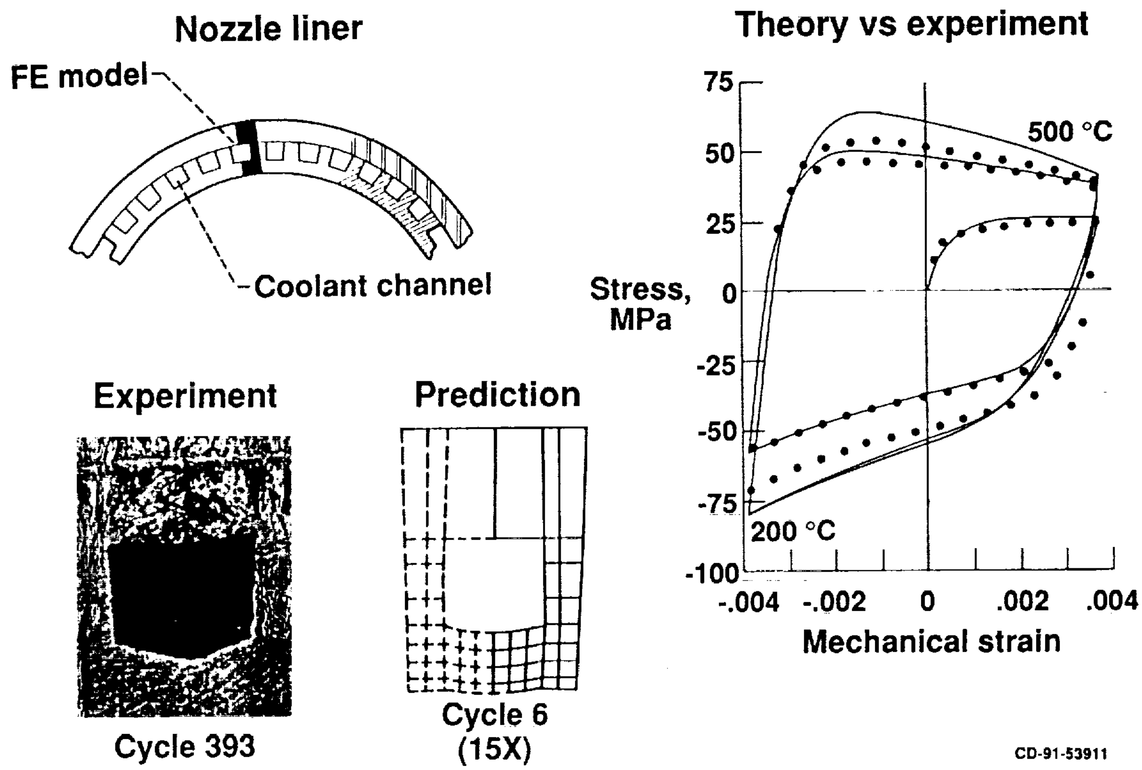
$$\dot{X} + UX = V$$

the linear, asymptotic, recursive, integration algorithm is given by

$$X(t + \Delta t) = X(t)e^{-U(t + \Delta t)\Delta t} + V(t + \Delta t)\left[\frac{1 - e^{-U(t + \Delta t)\Delta t}}{U(t + \Delta t)}\right]$$

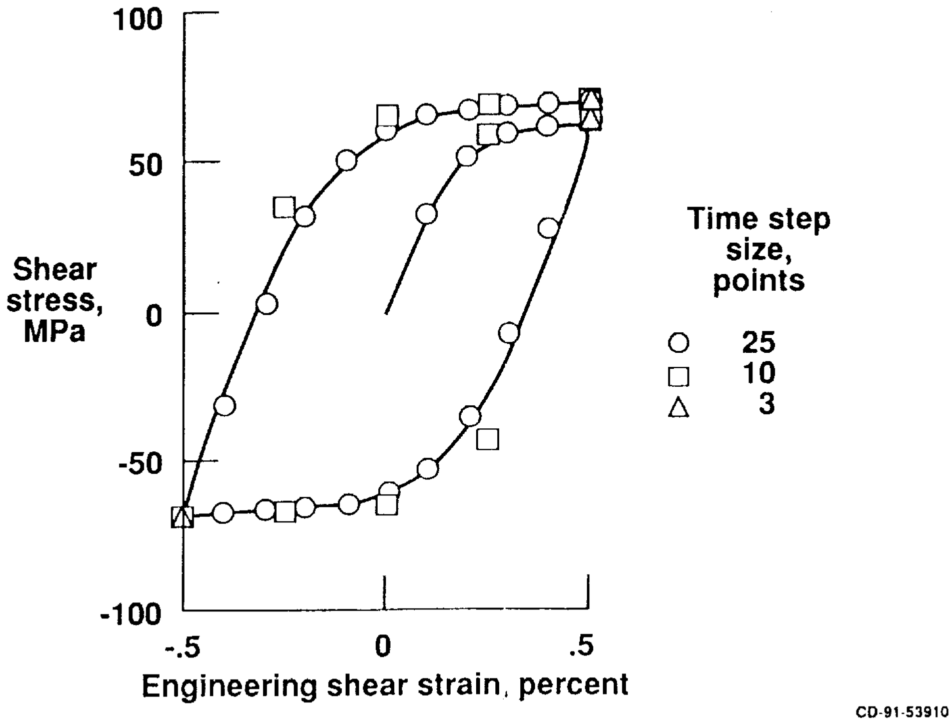
An example of the applicability of this integration algorithm for various time step sizes is shown here. Achieving equal accuracy using the classical method of Runge-Kutta (well suited for stiff differential equations) would require on the order of 10 000 time steps.

Finite Element Analysis



Viscoplastic models are complex. The choice of an existing model, or the development of a new one, will depend on both the selected material and its intended application. One must know what the dominate material behaviors are for the selected material. Then one must determine which of these dominate material characteristics will manifest themselves in the intended application and which ones will not. The simpler the model, the better it is. Once a model is chosen and the material is characterized, the model can be implemented into a finite element code, thereby allowing a structural analysis of the intended application to be made. An example of this procedure is given for an engine nozzle liner. In applications the nozzle liner ratchets, causing a thinning of the liner and its eventual rupture. A viscoplastic analysis of the nozzle is in qualitative agreement with this observation.

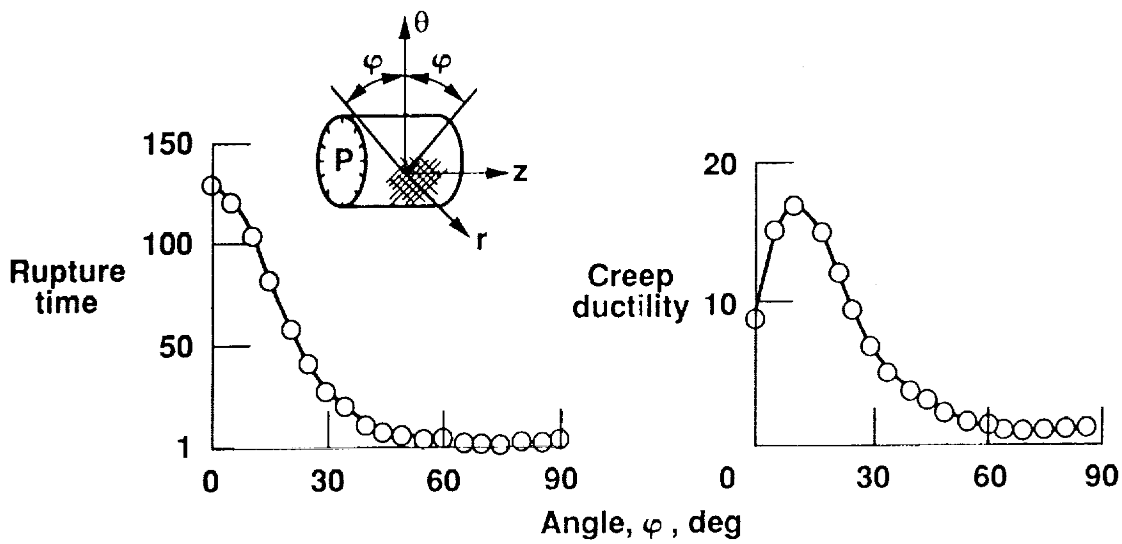
Numerical Integration Development



High-temperature fatigue data for metallic and intermetallic matrix composites, MMC's and IMC's, are very scarce. In the search for a correlating parameter for fatigue, Bartolotta (of NASA Lewis) recently proposed a maximum strain model for fibrous composites. The data presented here are for SiC/Ti-24Al-11Nb at 425 and 815 °C. There appears to be no dependence on the mode of loading when this correlating parameter is used. Region I is defined by the tensile ductility range and represents the domain where composite strength is dictated by fiber strength. Region II defines a progressive fatigue domain, where a decrease in the maximum strain leads to an increase in the fatigue life. This region is temperature dependent. Region III defines what appears to be a fatigue limit for the composite.

Creep Rupture

Damage Mechanics of Composites



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Continuum damage mechanics was originally developed for modeling creep rupture and works well for that purpose. In work supported by NASA Lewis a continuum damage mechanics model has been developed for modeling creep rupture in fibrous composites that have elastic fibers and a viscoplastic matrix. The model was developed by using an isochronous damage function, which is assumed to depend on the invariants specifying the maximum tensile stress normal to a fiber and the maximum longitudinal shear stress along it. These stress components lead to damage in the composite at the fiber-matrix interface and eventually cause creep rupture. The theory has been applied to thin-wall pressure vessels having one and two families of helically oriented fibers. The results shown are for two fiber families. Results for one fiber family are similar, with the maximum creep ductility shifted out to a fiber angle of about 30°.

SUMMARY

- Metals at elevated temperature exhibit complex, inelastic, hereditary behavior.
- Over the past decade through the HOST, SSME, and HITEMP programs, NASA Lewis has advanced the state of the art in viscoplastic analysis and experimentation.
- The theoretical, computational, and experimental personnel at Lewis have extensive and unique experience in the following areas:
  - High-temperature experimentation
  - Thermomechanical fatigue
  - Life assessment
  - High-temperature structural analysis
  - Viscoplastic constitutive modeling
  - Composite mechanics